

# **Optical Variability and Bottom Classification in Turbid Waters: Phase III**

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## **LONG-TERM GOALS**

Real-time determination of the optical and bathymetric climate available for operation of various Navy and Coast Guard assets in the coastal zone using a mixture of AUV, ROV, surface-vessel, fixed moorings/towers, and air/space-borne observational assets. This includes advanced heat-budget modeling applicable to coastal regions, methods for early detection of *K. brevis* (red-tide) and other algal blooms, remote determination of optical properties (absorption and scattering) of the water, harmful algal blooms, depth and bottom albedo. These provide model inputs and validation data for predicting visibility and the performance of optical systems as well as heat budget and primary production models, useful in asset selection for Homeland Security operations.

## **OBJECTIVES**

The development of optical methodologies valid for Case II coastal waters for the remote determination of water and bottom optical properties including visibility, water and bottom optical absorption, algal concentrations, bathymetry, bottom albedo, vegetation cover, and bottom structure are being pursued. These include interpretation of hyperspectral, high-resolution imagery from aircraft and satellites, development and deployment of suites of small instruments on remotely operated and autonomous underwater vehicles (ROVs, AUVs) and a multi-disciplinary network of moored sensors. Data are used in development/application of radiative transfer models and algorithms for predicting optical properties and extracting information from the remote data. Effects of vertical structure in the optical properties (e.g. river plumes, suspended sediments) and turbidity must be recognized for the data retrievals to be accurate, and the instruments and methodologies necessary to quantify such structure are being developed and utilized on underwater vehicles and moorings.

The focus for our work this year continues to be in direct response to the September 11 attacks on the United States and the call for increased attention to Homeland Security with an emphasis on Port Security. We have accelerated our efforts toward the quantification of performance parameters for underwater imaging systems and for now-casting the optical properties of the water column at scales appropriate to application in Homeland Security strategies.

## **APPROACH**

Models have been developed for inverting hyperspectral data from air- and space-borne sensors in vertically homogeneous waters to more accurately estimate absorption, back-scattering, and beam-attenuation coefficients (e.g. see Lee et al. 2002, 2004; Liu et al. 2002; Carder et al. 2004, 2005;

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Cannizzaro and Carder 2005), as well as bathymetry and bottom albedo (e.g. Carder et al. 2003 and PUBLICATIONS). We have also presented methodologies for advanced coastal-water heat budget modeling (Warrior et al. 2002; Warrior 2004; Warrior and Carder, 2005) and early detection of red-tide and other algal blooms (Cannizzaro et al. 2004, 2005, Cannizzaro et al. submitted). These can be used as initial or boundary conditions for heat-budget, primary production and visibility models and to predict where certain mine-counter-measure assets can productively be deployed given sensor-performance models.

To more accurately invert data from airborne, hyper-spectral sensors such as PHILLS, we have vicariously calibrated the sensor and atmospherically corrected the data with inversion provided by parameter optimization modified by a genetic code (Chen et al. 2004). This prevents the solution from being “trapped” in a local rather than a global minimum for each parameter. As such sensors and methods improve for more-turbid waters, utility for measuring denied-access regions increases.

To invert coastal data from existing ocean-color satellites (e.g. SeaWiFS, MODIS, MERIS, etc.) that don’t provide hyperspectral data, a method was developed to identify pixels contaminated by bottom effects and to provide a first-order correction for bottom effects for waters at least 5m deep (Carder et al. 2005; Cannizzaro, Carder and Lee submitted). Using accurate, synthetic  $R_{rs}$  data, log-based root-mean-square errors for backscattering were reduced from 47% to 6% and for chlorophyll (particle-absorption proxy) were reduced from 28% to 16% by selecting algorithm bands that straddle the transparency window. Specifically, accurate data for wavelengths greater than about 615 nm are recommended.

Water clarity, bathymetry, and bottom albedo are critical variables affecting optical searches for objects in the water column or on the bottom. Object contrast with the background optical fields (e.g. English et al. 2005) or its 3-dimensional shape (Carder et al. 2003) can be used in object-and bottom-classification schemes. Using elastic and inelastic scattering and active and passive imaging systems, we are evaluating how system performance degrades with increased turbidity, range, and optical structure (e.g. layers) for a variety of bottom types (Hou et al, 2002) and beneath underwater structures, e.g. ship hulls (Reinersman and Carder, 2002; 2004). Sensor performance models require combinations of ambient-light models (Reinersman and Carder, 2004; Carder et al. 2005) and laser-line-scanner models (Montes-Hugo et al. 2005; Montes-Hugo 2005).

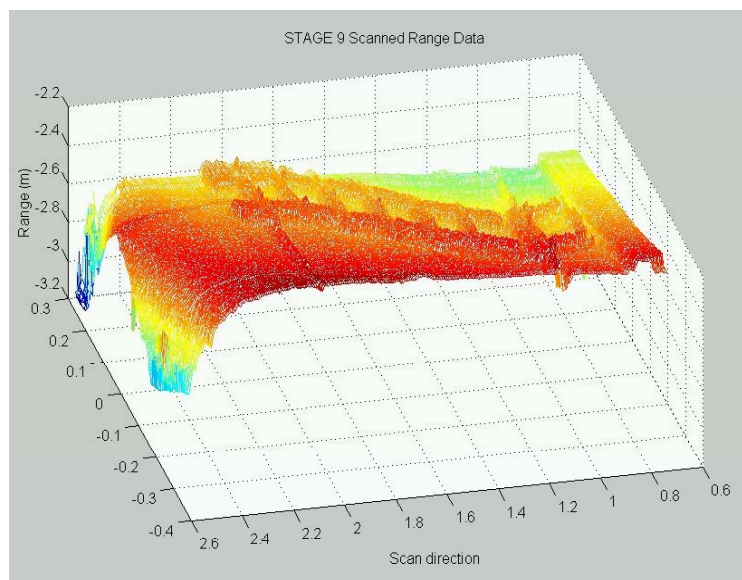
Several optical packages have been developed for deployment on ROVs and AUVs to measure the optical properties of the water column and bottom to provide an assessment of the accuracy of the model assumptions and retrieval values from air-borne sensors, and we have deployed these as part of the CoBOP and HYCODE field activities. Several [e.g. Bottom Classification and Albedo Package, BCAP, Real-Time Ocean Bottom Optical Topographer, (ROBOT), and the Mobile Inspection Platform (MIP)] have been developed and tested on ROVs or AUVs including our ROSEBUD remotely operated vehicle (ROV), the Ocean Explorer class autonomous underwater vehicles, and USF's Center for Ocean Technology (COT) ROVEX vehicle (Carder et al., 2001, 2003; Costello and Carder, 1997; Costello et al., 1998a, 1998b; Renadette et al., 1997, 1998). Validation of 2-D and 3-D environmental optical models for light fields beneath ships (Reinersman and Carder 2004), are tasks to which these systems are ideally suited and have been applied (Carder et al. 2005).

## WORK COMPLETED

Oceanography is inherently a multi-disciplinary science and our group is a team of oceanographers dedicated to developing optical methodologies that address real-world applications. These efforts require acquisition of extensive field data (above and below the surface) and extensive modeling. Analysis and comprehensive interpretation of field data and model results require us to address physical, biological, chemical, and geological processes which affect water optics. The range and success of our work, then, is most directly presented via our list of 30 publications (19 refereed) produced by our group during 2004 - 2005. Please refer to the **PUBLICATIONS** section below.

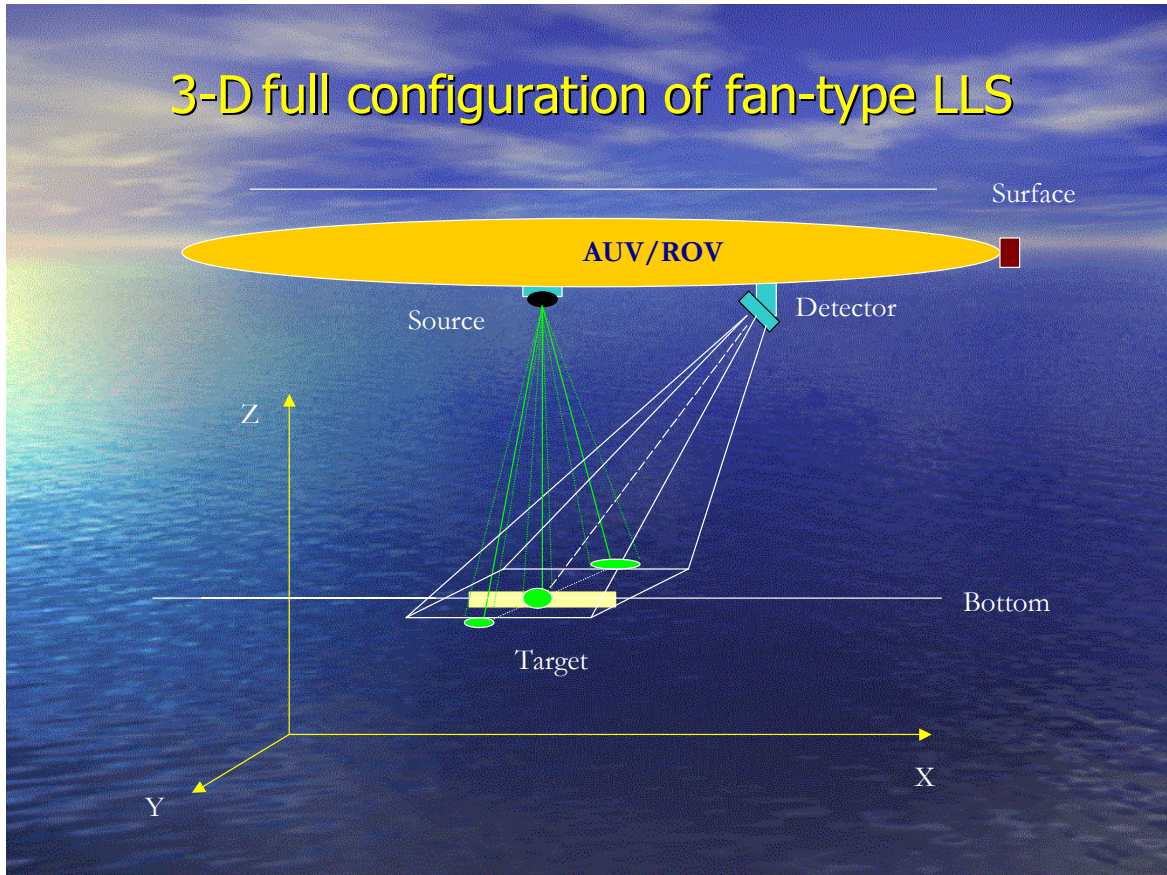
## RESULTS

Elastic and inelastic 3-D images for inspection of ship hulls were acquired by inverting the ROBOT system (a prototype for the Mobile Inspection Platform) on our ROSEBUD ROV in the relatively turbid water ( $c532 \approx 3.0/\text{m}$ ) of Tampa Bay. 2-Way maximum ranges of 18 e-folding lengths were determined in the elastic mode and 12 e-folding lengths in the fluorescence mode using the Xybion intensified camera as a receiver. Fluorescence-mode imagery would be most useful in highly scattering waters because of the elimination of on-line path radiance. The fluorescence mode would also be useful, for example, in detecting a recently attached object (e.g. a limpet mine) on a ship hull since the recent object would not have sufficient algal growth to fluoresce. Figure 1 shows a 3-dimensional fluorescence image acquired during the Submerged Target Aging Experiment (Stage). The (inverted) image is of the hull of a small boat to which a pair of targets were added each week. Note that the targets were painted flat black and would not necessarily reflect highly enough to be visualized in a reflective mode.



***Figure 1. A 3-dimensional laser-line image acquired in the fluorescence mode. Note that the image is possible because of fluorescence of algal scum on the boat hull and aged targets. The targets consisted of sections of PVC pipe that were painted flat black and not likely to be visualized in a reflective mode.***

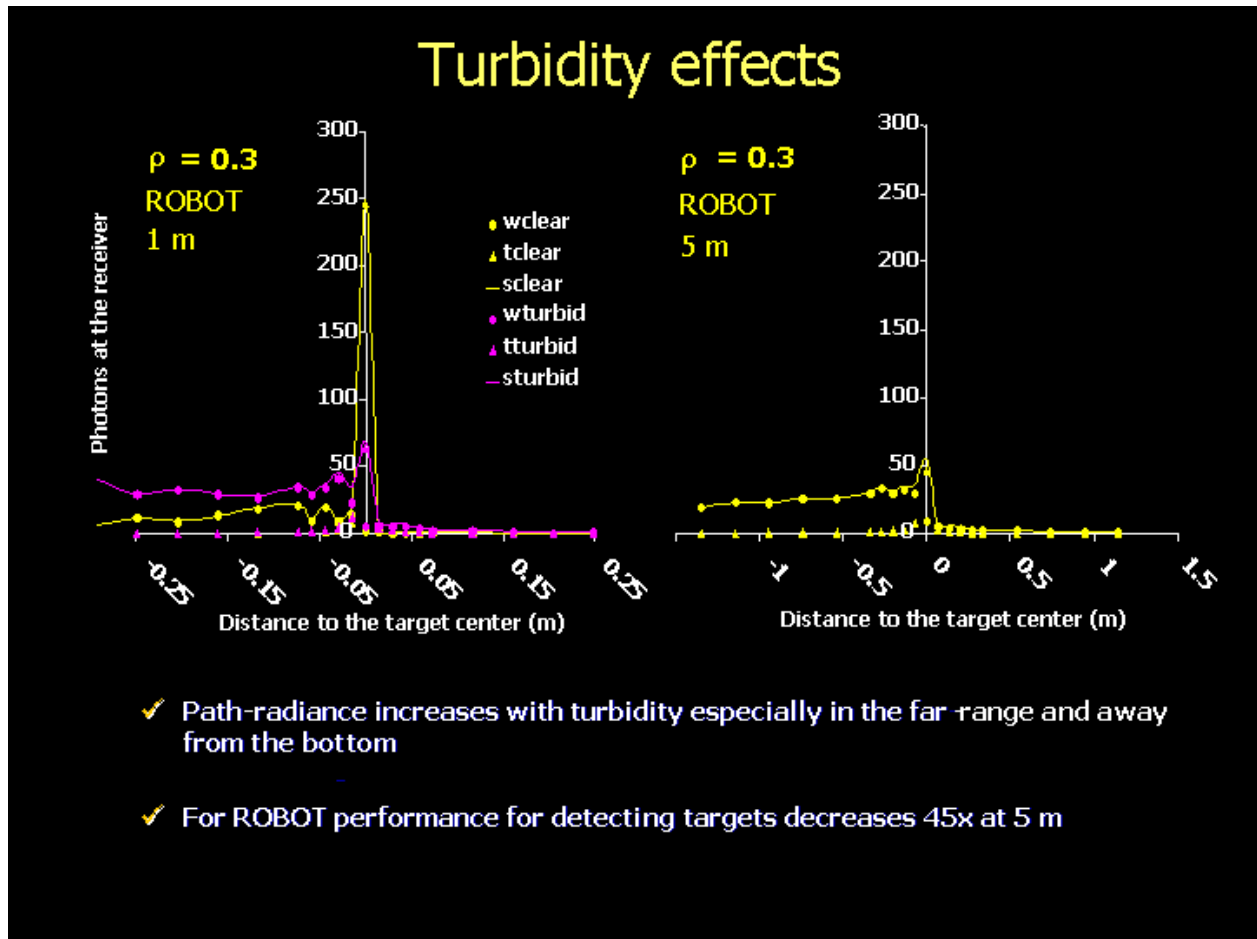
Signal contributions from path radiance reduce the accuracy of ROBOT-derived albedos. Recently, we developed a Monte Carlo model of ROBOT performance to evaluate the fate of elastic photons in a nocturnal environment (Montes-Hugo et al. 2005; Figs. 2, 3). For use beneath ships or at depth in the ocean where ambient light is prevalent, the sensor model results will be added to results from the 3-D Hybrid Marine Optical Model (HyMOM; Reinersman and Carder 2004; Carder et al. 2005). They provide a means of selecting strategies for ROBOT sensor deployment and for data interpretation.



**Figure 2. Schematic of ROBOT used in Monte Carlo simulations to optimize use in turbid waters. A laser fan is projected downward and observed from an angle. Bi-static separation distance between source line and detector is variable.**

Red-tide blooms with chlorophyll *a* concentrations greater than 2-3 mg/m<sup>3</sup> or 10,000-20,000 cells/liter can be discriminated and quantified from space-craft or aircraft ocean-color data by both chlorophyll-specific backscattering and fluorescence (Cannizzaro et al. 2004, 2005). Concentrations as high as 130 mg/m<sup>3</sup> were quantified by MODIS using fluorometric remote sensing. Large red tides can result in anoxic, black-water events as we observed in 2002 (Neeley et al. 2004; Hu et al. 2002), affecting not only breathing, but also visibility for swimmers. We observed red tides off Tampa Bay from January through August both remotely with MODIS and SeaWiFS, but also with R/V Subchaser cruises at both ends of the event. The August cruise produced black water data near the bottom, with near-anoxic conditions, low light, and anomalous pigment suites, absorbing in the near infrared. Research is continuing on this data set.

The Autonomous Marine Optical System (AMOS; Steward and Carder 2002) was set up on a piling in Bayboro Harbor where weekly validation data could be easily collected. Data such as those shown in Figure 4, are being evaluated by a student for a master's thesis. The remote-sensing reflectance data provide IOPs by model inversions that are compared to AMOS IOP measurements and field samples collected nearby. Dry-wind events increase the turbidity but not the chlorophyll, with chlorophyll increasing some 3 days later. This suggests a nutrient release from suspended sediments containing little or no benthic diatoms or other algal cells. AMOS-type sensors can provide calibration and validation data for satellite and aircraft remote sensors, which is especially useful to help with atmospheric corrections in turbid, coastal waters where water-leaving radiance in the infrared is non-zero.

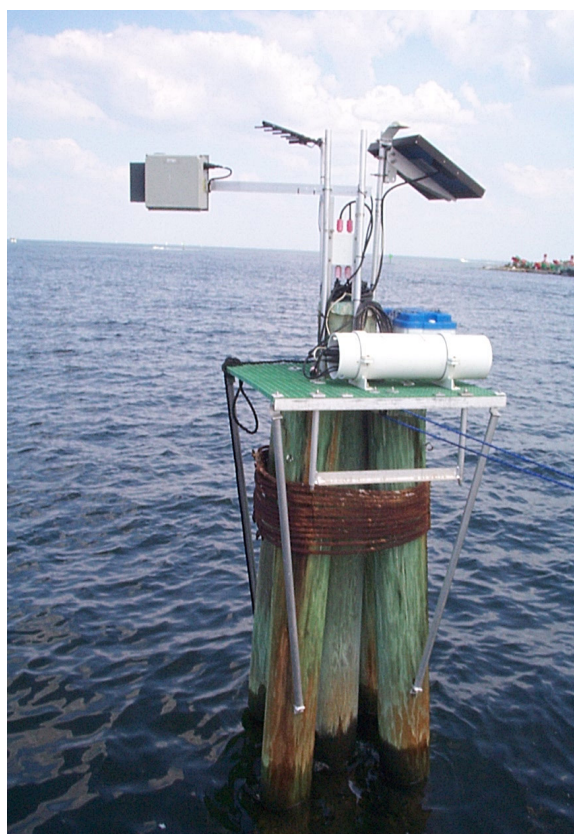


**Figure 3.** The path radiance is a minor contribution to the center, laser-line pixel, amounting to less than 20% even with a 5 m range in clear water ( $c = 0.22 \text{ m}^{-1}$ ) and a 1 m range in turbid water ( $c = 1.0 \text{ m}^{-1}$ ). With multiple cross-track pixels, even this contribution can be estimated and corrected. Near-range baseline is less than 10% of peak value, allowing laser-line position to be detected and triangulated for 3-D imaging, and bottom albedo to be corrected for path radiance.

Several very turbid rivers that we have sampled flow into Tampa Bay (Alafia, Hillsborough, Palm River) and the Gulf of Mexico (Caloosahatchee). These are “black-water” or CDOM-rich rivers, with CDOM absorption values at 400 nm sometimes reaching  $20 \text{ m}^{-1}$ , detrital absorption values at 400 nm reaching  $8 \text{ m}^{-1}$ , and chlorophyll *a* values reaching  $60 \text{ mg m}^{-3}$ . These high values can be seasonal, and

vary widely. Remote sensing and modeling of these types of rivers can be performed to estimate visibility and light penetration, “cloaking” of certain operations, and sensor performances (e.g. Fig. 3). These rivers differ markedly from sediment-laden rivers such as the Mississippi inasmuch as visibility is typically absorption-limited rather than scattering- limited. This suggests that adequate source illumination at the absorption minimum of about 560 nm may permit operations requiring some visual acuity.

Optical modeling of CDOM-rich waters poses a different problem than for most marine situations. CDOM fluorescence (usually considered negligible) can be so large that it affects  $R_{rs}$  spectra not only at blue wavelengths (see Fig. 6), but also out to red wavelengths. Note that the fluorescence trace of the chlorophyll *a* fluorometer at 685 nm shown in Figure 7 varies inversely with salinity as does CDOM absorption, but varies inversely rather than directly with extracted chlorophyll *a* concentrations. The implication is that for CDOM fluorescence at 685 nm increases more rapidly than chlorophyll *a* fluorescence decreases when sampling going up the Alafia River away from the chlorophyll maximum at the mouth and toward the CDOM maximum at 0 psu salinity. A later test in a laboratory chlorophyll fluorometer of an aliquot of this river water, filtered through a 0.2 micron diameter filter, provided fluorescence values equivalent to about 2 mg m<sup>-3</sup> chlorophyll *a*.



### ***Autonomous Marine Optical Sensor Network (AMOS)***

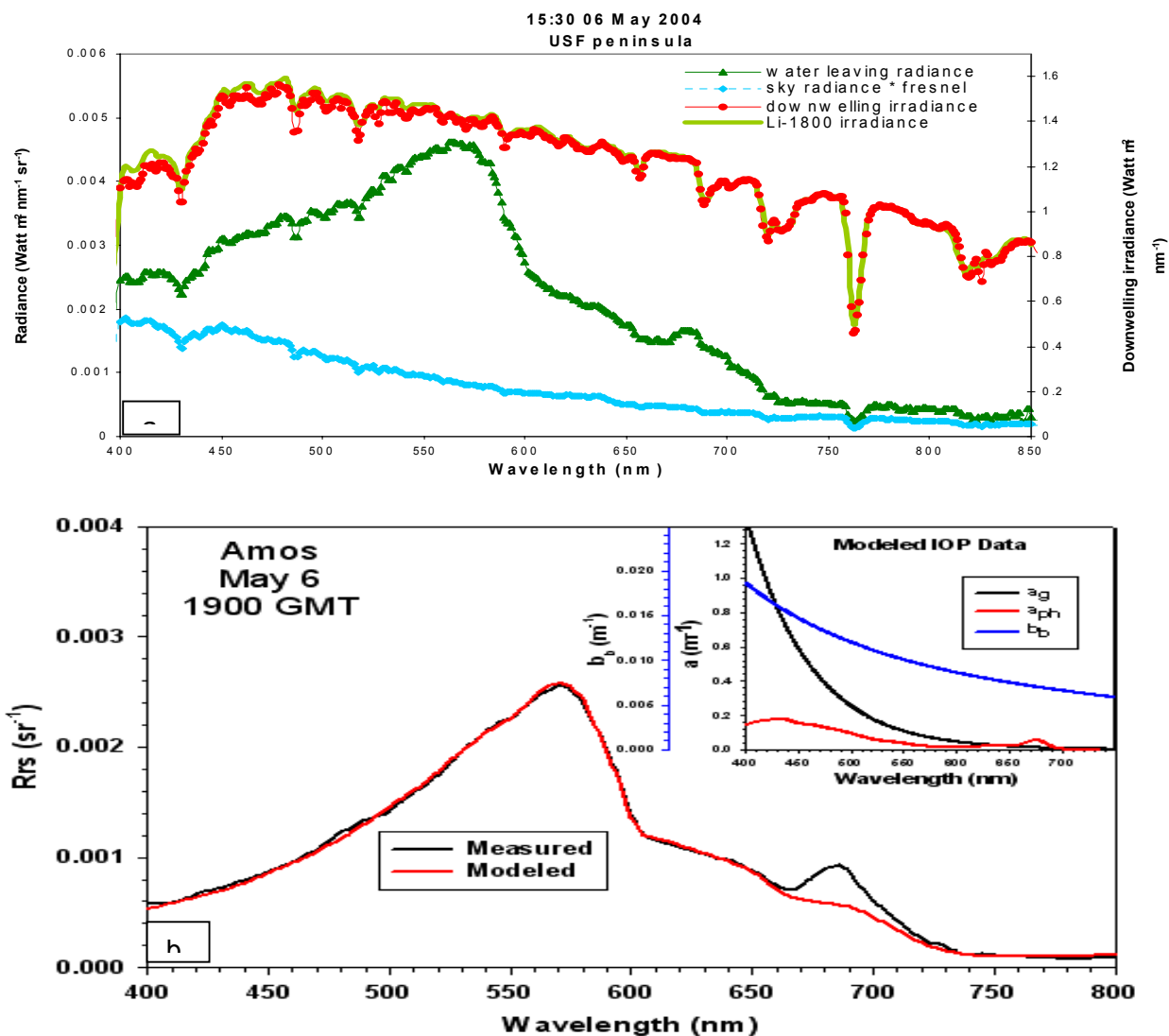
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***Figure 4. Above-water components  
of AMOS as deployed in the  
USF/Bayboro Harbor site. The  
above-water radiometer is the gray  
box extending above the water to the  
left in this image.***

The present model of fluorescence efficiency for marine CDOM (Hawes 1992) used in Hydrolight (Mobley 1994) does not provide emission values for excitation values longer than 490 nm, the limit measured by the apparatus used by Hawes. Whether riverine CDOM differs significantly from marine CDOM or a simple extension of the Hawes (1992) curves is required to explain this phenomenon needs evaluation. Without an adequate understanding of CDOM fluorescence for CDOM-rich waters, model inversions of  $R_{rs}$  curves to derive inherent and apparent optical properties for such waters (e.g. Fig. 5b) will be unsuccessful or inaccurate.

## **IMPACT/APPLICATIONS**

We discussed our use of active and passive stimulation of bottom fluorescence from natural, algae-rich surfaces and the indication that regions devoid of fluorescence were observed for animals and recently deployed, man-made objects. We have continued this work for application to inspecting both ship hulls and vertical underwater structures (e.g. pilings, sea walls) that are of interest in Port Security. Ships spending considerable time in turbid waters are found to lose their fluorescence signature, however, so the optical history of a ship can affect the interpretation of these signatures.



**Figure 5. a) Down-welling irradiance, sky radiance, and water radiance measured by AMOS; b) remote-sensing reflectance ( $R_{rs}$ ) derived from (a) and the absorption and backscattering constituents derived by model inversion (e.g. Lee et al. 1999). Note that AMOS uses a common spectrometer with three fiber-optic pathways that are switched automatically. This provides a smooth  $R_{rs}$  curve for the ratios, even over the jagged Fraunhofer lines apparent in (a). The underwater sensors of AMOS contribute diffuse attenuation, beam attenuation and chlorophyll and CDOM fluorescence values. Large-scale maps of water properties and bottom depth and albedo are critical in the assessment of visibility, navigability, and underwater sensor performance. In the same vein, the ability to detect harmful algal blooms from space or aircraft-borne sensors is important to both economic and security concerns.**

## TRANSITIONS

Our red-tide detection algorithm has been transitioned to NOAA Coast Watch.

## RELATED PROJECTS

This project has a close association with the ROBOT project (Kaltenbacher et al., this volume). ROBOT is an AUV/ROV deployed, laser-line imaging system designed to produce 3-dimensional maps of underwater surfaces (bottoms, seawalls, hulls, etc.) We are utilizing our methodologies and hardware to quantify and predict performance parameters for both the on-line and fluorescence (see RESULTS) modes of operation of the ROBOT systems well as to develop algorithms for automatic (computerized) target recognition.

We are also collecting field data regarding the structure of the underwater light field around objects (e.g. ship and seawall shadows) under various environmental conditions for the validation of the “Hybrid Modular Optical Model To Predict 2-D and 3-D Environments in Ports...” (HyMOM, ONR, Carder and Reinersman, this volume).

We are actively supporting three ONR projects headed by John Kloske, USF Center for Ocean Technology, and Scot Tripp, US Coast Guard Research and Development Center, toward utilizing our methodologies along with imaging sonar toward improving fleet and Homeland Security. These projects include Advanced Underwater Port Security Systems and the Development and Evaluation of the Mobile Inspection Platform, first deployed on our ROSEBUD ROV. The ROV has also been used for evaluation deployments of the ISS ranging camera and Echoscope and Tritech Mini-king imaging sonars (Steve Lawrance, Subsea Technologies, Inc.) as well as the Coda Echoscope 1600 3-D Real Time acoustic sonar (Angus Ludsdin, Codaoctopus, Ltd.)

Efforts within our group toward model inversion (funded through ONR and NASA) utilizing remote-sensing reflectance, provides bathymetry and water optical properties. Most recently, efforts have been focused on providing sea-truth and image interpretation for the PHILLS hyperspectral imaging sensor owned by NRL Washington (Curtiss Davis) and operated by Paul Bissett, Florida Environmental Research Institute.

Finally, this project benefits from the database acquired during the ONR programs Coastal Benthic Optical Properties (CoBOP, Carder and Costello) and HyCODE field campaigns and multi-agency program ECOHAB.

## REFERENCES

*Note: citations above not presented here are included in our current PUBLICATIONS section below.*

Carder, K.L., C.C. Liu, Z. Lee, D.C. English, J. Patten, F.R. Chen, J.E. Ivey, and C. Davis. (2003). Illumination and turbidity effects on observing faceted bottom elements with uniform Lambertian albedos. *Limnol. Oceanogr.*, 48(1), 355-363.

Carder, K.L., D.K. Costello, L.C. Langebrake, W. Hou, J.T. Patten, and E.A. Kaltenbacher, 2001. Real-time AUV data for command, control, and model inputs. *IEEE Jour. of Ocean Eng.* 26(4): 742-751.

- Costello, D.K., K.L. Carder, and J.S. Patch. 1998a. Methods for Utilizing Hyperspectral In-situ Light Profiles in the Presence of Wave Focusing and the Absence of Above-water Measurements. EOS AGU/ASLO.
- Costello D.K., K. L. Carder, W. Hou, T.G. Peacock, and J.E. Ivey. 1998b. Hyperspectral Measurements of Upwelling Radiance During CoBOP: the Role of Bottom Albedo and Solar Stimulated Fluorescence. Ocean Optics XIV. Kailua-Kona.
- Costello D.K. and K. L. Carder. 1997. In situ optical data collected aboard unmanned underwater vehicles in coastal water. ASLO 97. Santa Fe.
- Hawes, S.K. 1992. *Quantum Fluorescence Efficiencies of Marine Fulvic and Humic Acids*, M.S. thesis, Department of Marine Science, University of South Florida, 92 p.
- Hou, W., K. L. Carder, and D. K. Costello. 2002. Coastal Bottom Feature Classification Using 2-D and 3-D Moment Invariants. (*Ocean Optics XVI*).
- Hu, C., F. Muller-Karger, Z. Lee, K. Carder, et al. (2002). Satellite images track “black-water” event off the Florida coast. *EOS Trans. Amer. Geophys. Un.*, 83(26), 281, 285].
- Lee, Z. P., K. L. Carder and R. Arnone. (2002). Deriving Inherent Optical Water Properties From Water Color: A Multi-Band Quasi-Analytical Algorithm for optically deep waters. *Applied Optics*, 41(27), 5755-5772.
- Liu, C. C., K. L. Carder, R. L. Miller and J. E. Ivey. (2002). Fast and accurate model of underwater scalar irradiance. *Applied Optics*, 41(24), 4962-4974.
- Mobley, C.D. 1994. *Light and Water: Radiative Transfer in Natural Waters*, Academic, San Diego, 592 p.
- Reinersman, P. N. and K. L. Carder, 2002, A modular, hybrid method for solving the radiative transfer equation with arbitrary geometry in 1, 2, or 3 dimensions. In *Ocean Optics XVI*, S. Ackleson and C. Trees (eds.), Office of Naval Res. CDROM, Arlington, VA, 6 p.
- Renadette, L.A., K.L. Carder, D.K. Costello, W. Hou, and D.C. English. 1998. Characterization of Bottom Albedo Using Landsat TM Imagery. EOS AGU/ASLO.
- Renadette, L.A., K.L. Carder, D.K. Costello, and W. Hou. 1997. AUV Data: Interpretation in Terms of Aircraft and Satellite Imagery. ASLO 1997, Santa Fe.
- Steward, R. G. and K. L. Carder, 2002, Compression Of Autonomous Hyperspectral Data. . *Proceedings, Ocean Optics XVI*, Santa Fe, NM, Office of Naval Res. CDROM, Arlington, VA, 6 p.
- Warrior, H., K. L. Carder, Z.P.Lee, D. Otis and R. Chen. 2002. An improved optical model for heat and salt budget estimation for general ocean circulation models. In *Ocean Optics XVI*, S. Ackleson and C. Trees (eds.), Office of Naval Res. CDROM, Arlington, VA, 6 p. [published]

## PUBLICATIONS

- Cannizzaro, J.P., K.L. Carder, F.R. Chen, J.J. Walsh, Z.P. Lee, and C.A. Heil, 2004. A novel optical classification technique for detection of red tides in the Gulf of Mexico, 2004. In: *Harmful Algae 2002*, Steidinger et al., eds., Florida Marine Research Institute, Florida Institute of Oceanography, UNESCO, St. Petersburg, FL, pp. 282-284. [published, refereed].
- Cannizzaro, J.P., K.L. Carder, F.R. Chen, C.A. Heil, and G.A. Vargo, 2005. A novel technique for detection of the toxic dinoflagellate, *Karenia brevis*, in the Gulf of Mexico from remotely sensed ocean color data, *Cont. Shelf Res.*[accepted, refereed].
- Cannizzaro, J.P., K.L. Carder, Z.P. Lee, Ocean color algorithms for optically shallow waters: limitations and improvements, submitted, *Remote Sens. Environ.* [submitted, refereed]
- Cannizzaro, J.P., Carder, K.L. 2005. Estimating chlorophyll *a* concentrations from remote-sensing reflectance data in optically shallow waters. *Remote Sens. Environ.* [submitted, refereed]
- Cannizzaro, J. P., K. L. Carder, F. R. Chen, J. J. Walsh, Z. Lee, and C. A. Heil. 2004. A Novel Classification Technique for Detection Of Red Tide Blooms in the Gulf of Mexico. [In: Steidinger et al., eds.], *Harmful Algae 2002, Proceedings, Xth International Conference on Harmful Algae*, pp 282-287. [published, refereed].
- Carder, K.L., Walsh, J.J., Cannizzaro, J.P. 2005. Hunting red tides from space in *Our changing Planets*, Cambridge University Press, in prep.
- Carder, K.L., Chen, F.R., Cannizzaro, J.P., Campbell, J.W., Mitchell, B.G. 2004. Performance of the MODIS semi-analytical ocean color algorithm for chlorophyll-*a*. *Advances in Space Research*, 33,1152-1159. [published, refereed].
- English, D.C., and K.L. Carder. 2005. Determining bottom reflectance and water optical properties using unmanned underwater vehicles under clear or cloudy skies, *J. Atmos. and Oceanic Tech.*, [accepted with revisions, refereed].
- Hu, C., Muller-Karger, F.E., Taylor, C., Carder, K.L., Kelble, C., Johns, E., Heil, C.A. 2005. Red tide detection and tracing using MODIS fluorescence data: A regional example in SW Florida coastal waters. *Remote Sensing of Environment*, 97, 311-321. [published, refereed].
- Lee, Z. and Carder, K. L. 2005. Hyperspectral Remote Sensing. In: *Remote Sensing of Coastal Aquatic Environments*. Springer, the Netherlands. [published, refereed].
- Lee, Z., Cdarecki, M., Carder, K.L., David, C.O., Stramski, D. and Rhea, W. J. 2005. Diffuse attenuation coefficient of downwelling irradiance: an evaluation of remote sensing methods. *Jour. Geophys. Res.* VOL. 110, doi:10.1029/2004JC002573. [published, refereed].
- Lee, Z.P., K.L. Carder, and K.P. Du, 2004. Effects of molecular and particle scatterings on the model parameter for remote sensing, *Applied Optics* 43(25): 4957-2004. [published, refereed].

- Lee, Z.P. and K.L. Carder, 2004. Absorption spectrum of phytoplankton pigments derived from hyperspectral remote-sensing reflectance, *Remote Sens. Environ.* 89: 361-368. [published, refereed].
- Lenes, J.M., J.J. Walsh, D.B. Otis, and K.L. Carder, 2005. Iron fertilization of *Trichodesmium* off the west coast of Barbados: A one-dimensional numerical model. *Deep-Sea Res.* 52: 1021-1041. [published, refereed].
- Montes, M.A., Carder, K., Brown, E., Foy, R.J., 2005. Estimating phytoplankton biomass and PAR attenuation in coastal waters of Alaska using airborne remote sensing. *Remote Sensing of Environment*, [submitted].
- Neeley, M.B., E. Bartels, J.P. Cannizzaro, K.L. Carder, P. Coble, D. English, C. Heil, C. Hu, J. Hunt, J. Ivey, G. McRae, E. Mueller, E. Peebles, and K. Steidinger, 2004. Florida's black water event, In: *Harmful Algae 2002*, Steidinger et al., eds., Florida Marine Research Institute, Florida Institute of Oceanography, UNESCO, St. Petersburg, FL, pp. 377-379. [published, refereed].
- Otis, D. B., K. L. Carder, D. C. English, and J. E. Ivey. (2004). CDOM transport from the Bahama Banks. *Coral Reefs*. [published, refereed].
- Reinersman, P. N. and Carder, K. L. 2004. Hybrid numerical method for solution of the radiative transfer equation in one, two, or three dimensions. *Applied Optics*. Vol 43, No. 13. [published, refereed].
- Warrior, H. and K.L. Carder, 2005. Production of hypersaline pools in shallow water by evaporation, *Geophys. Res. Lett.* 32, LXXXXX, doi: 10.1029/2005GL023078, 2005. [published, refereed].
- Cannizzaro, J.P. 2004. Detection and quantification of *Karenia brevis* blooms on the west Florida shelf from remotely sensed ocean color imagery. University of South Florida, Master's thesis.
- Carder, K.L., P. Reinersman, D.K. Costello, E. Kaltenbacher, J. Kloske, and M. Montes-Hugo, 2005. Optical Inspection of Ports and Harbors: Laser-Line Sensor Model Applications in 2 and 3 Dimensions, *SPIE Proceedings*, Orlando, March, 2005. [published].
- Carder, K.L., Chen, F.R., Cannizzaro, J.P., Bailey, S.W., and Werdell, P. J. 2004. Toward a climate-quality chlorophyll dataset: Global validation of a semi-analytical chlorophyll-*a* algorithm. *Ocean Optics XVI*, Fremantle, Australia. [published].
- Carder, K.L., Cannizzaro, J.P., Lee, Z. Ocean color algorithms in optically shallow waters: Limitations and improvements. *SPIE Optics and Photonics*, San Diego, CA. [published].
- Chen, F. R., D. K. Costello and K. L. Carder. 2004. Hyper-spectral retrievals of bottom depth and albedo using a genetic optimization code. *Proceedings: Ocean Optics XVII, Fremantle Australia*. [published].
- Farmer, A. S. 2005. Bottom Albedo Derivations Using Hyperspectral Spectrometry and Multispectral Video. University of South Florida, Master's thesis.

Malick, L.A. 2004. Light quality and phytoplankton viability. University of South Florida, Master's thesis.

Montes-Hugo, M.A. and K.L. Carder, 2005. Monte Carlo simulations as a tool to optimize target detection by AUV/ROV laser line scanners, *SPIE Proceedings*, Orlando, March, 2005.

Montes-Hugo, M.A., 2005. *Monte Carlo simulations as a tool to optimize target detection by AUV/ROV laser line scanners*, M.S. thesis, University of South Florida, Tampa, Florida.

Otis, D. B., K. L. Carder, D. C. English, J. E. Ivey , J. Patch, F. R. Chen, and H. Warrior, 2002, Using Seawifs Imagery And Optical Property Measurements To Investigate The Bahama Banks As A Source Of Gelbstoff To The Surrounding Deep Ocean. In *Ocean Optics XVI*, S. Ackleson and C. Trees (eds.), Office of Naval Res. CDROM, Arlington, VA, 6 p. [published]

Warrior, H. 2004. *Parameterization of the Light Models in Various General Ocean Circulation Models for Shallow Waters*, Ph.D. dissertation, Univ. of South Florida, Tampa, FL, 141 pp.

## **PATENTS**

U.S. Provisional Patent entitled "3-D Imaging System with Pre-Test Module" (USF ref. No. 03B066) filed April 1, 2003, Carder and Reinersman.

U.S. Utility Patent Application entitled "Method and Program Product for Determining a Radiance Field in an Optical Environment" filed August 25, 2004. Reinersman and Carder.